

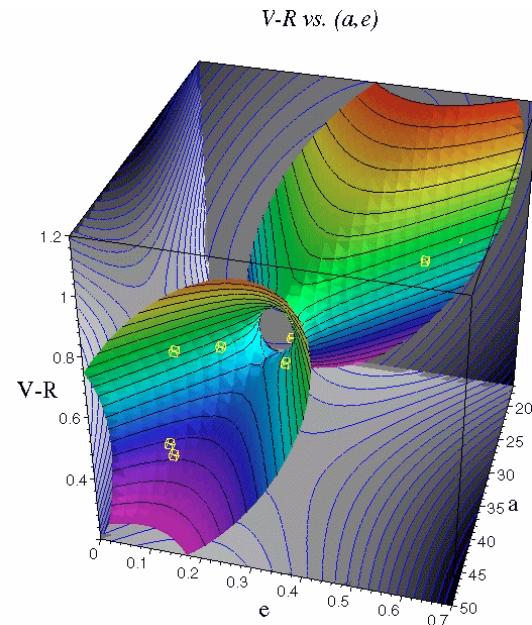
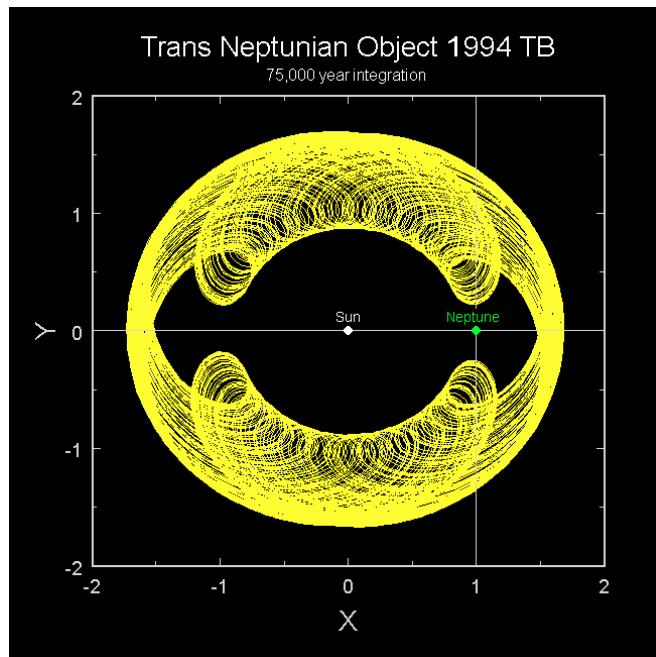
Trans-Neptunian Dynamics

An Extremely Brief Review

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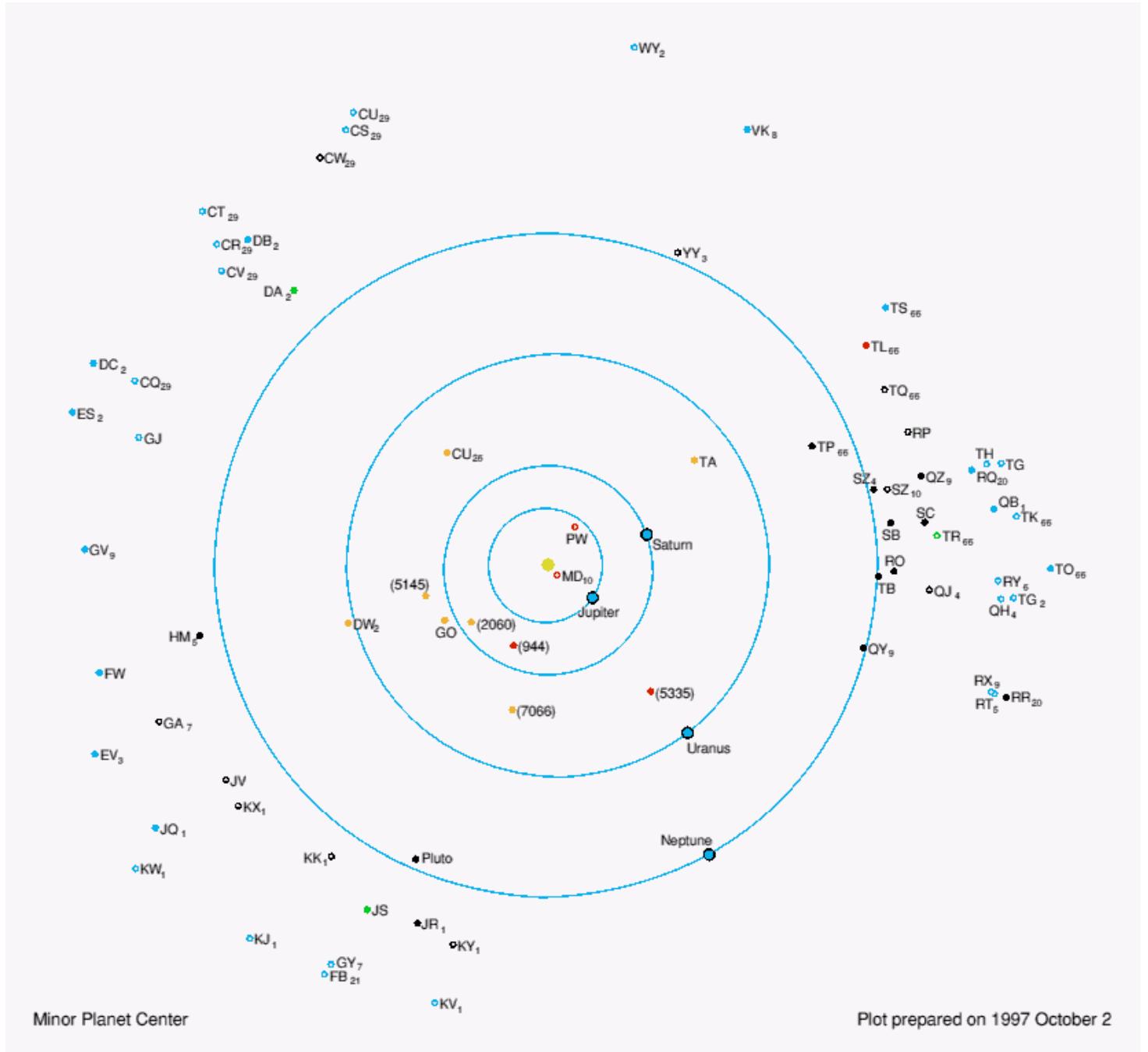
March 26, 1998



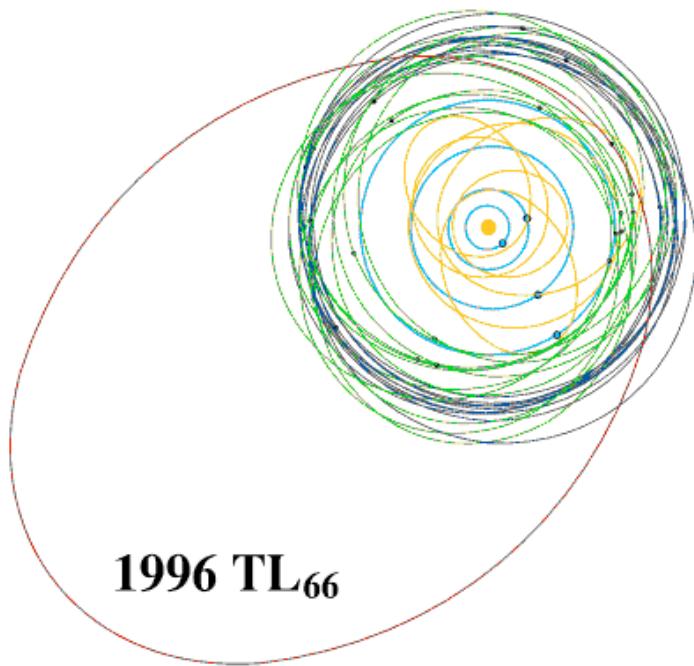
Trans-Neptunian Objects

- Often referred to as "Kuiper Belt Objects", or, more accurately, as "Edgeworth-Kuiper Belt Objects".
- $a > a_{\text{Neptune}} = 30 \text{ AU}$
- Large population of objects.
 - >70,000 with $D > 100 \text{ km}$
- Represent primitive objects from early accretional phases of the solar system.
- Kuiper Belt serves as reservoir of short-period comets (SPCs).
- Colors
 - Spectra range from nearly flat to very red
 - Broadband: two distinct populations!
- Centaurs:
 - 9 found so far, with semimajor axes ranging from 11.8 to 27.0 AU.
 - TNOs caught in transition to becoming SPCs.

The Outer Solar System



The Orbit of 1996 TL₆₆

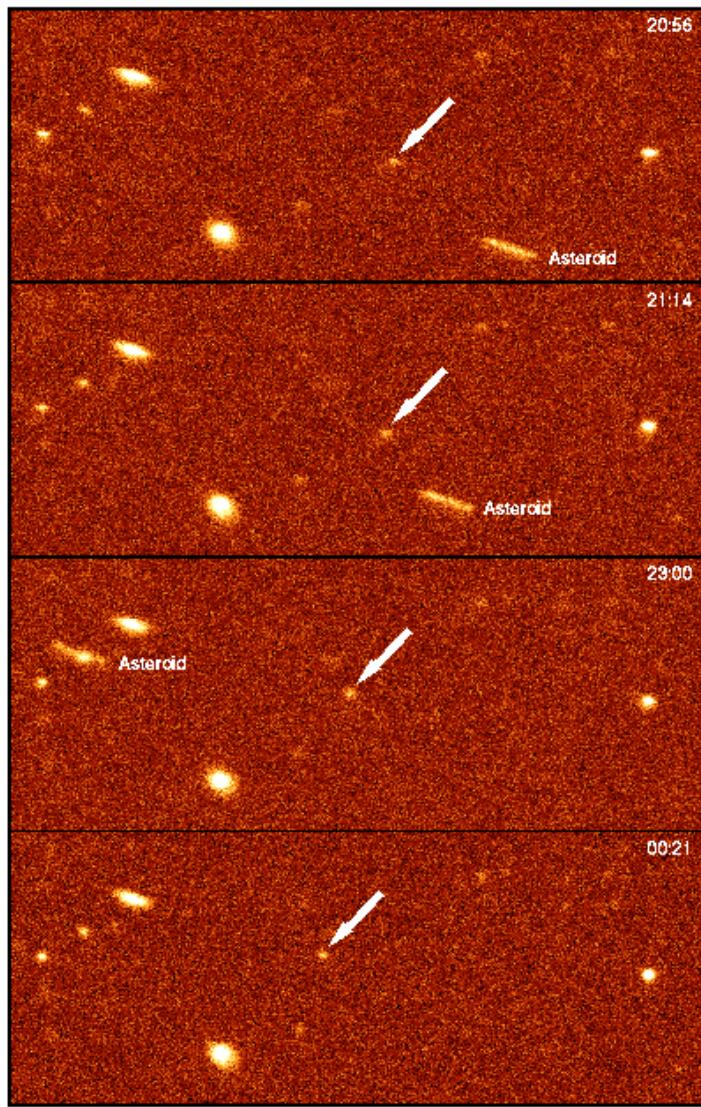


Minor Planet Center

Plot prepared on 1997 June 5

Trans-Neptunian Objects

- First one discovered in 1992 (1992 QB₁)



TNO Spectra

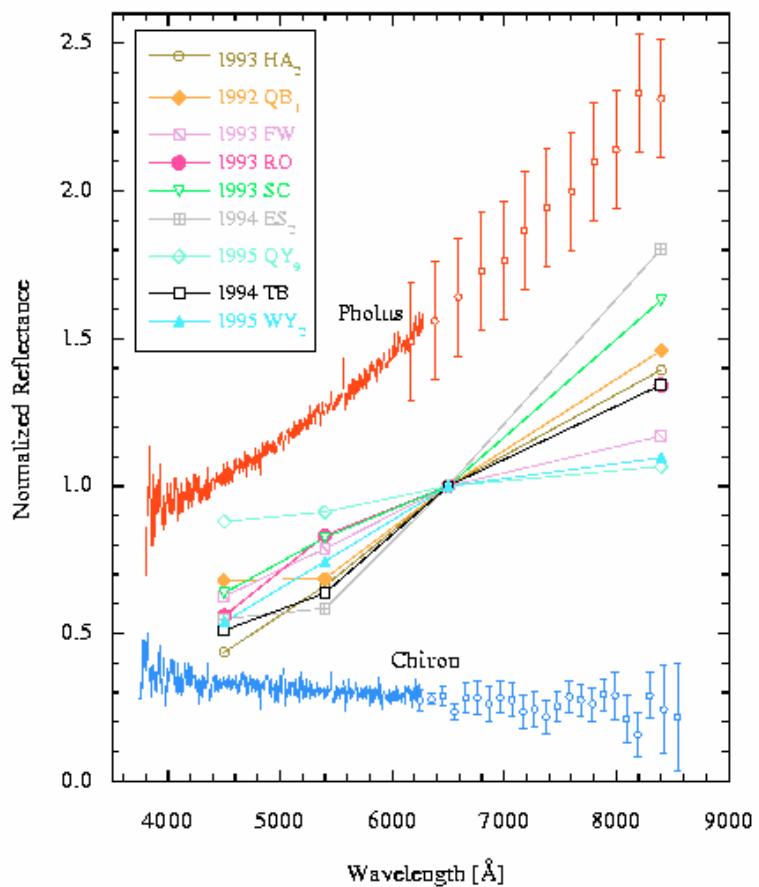
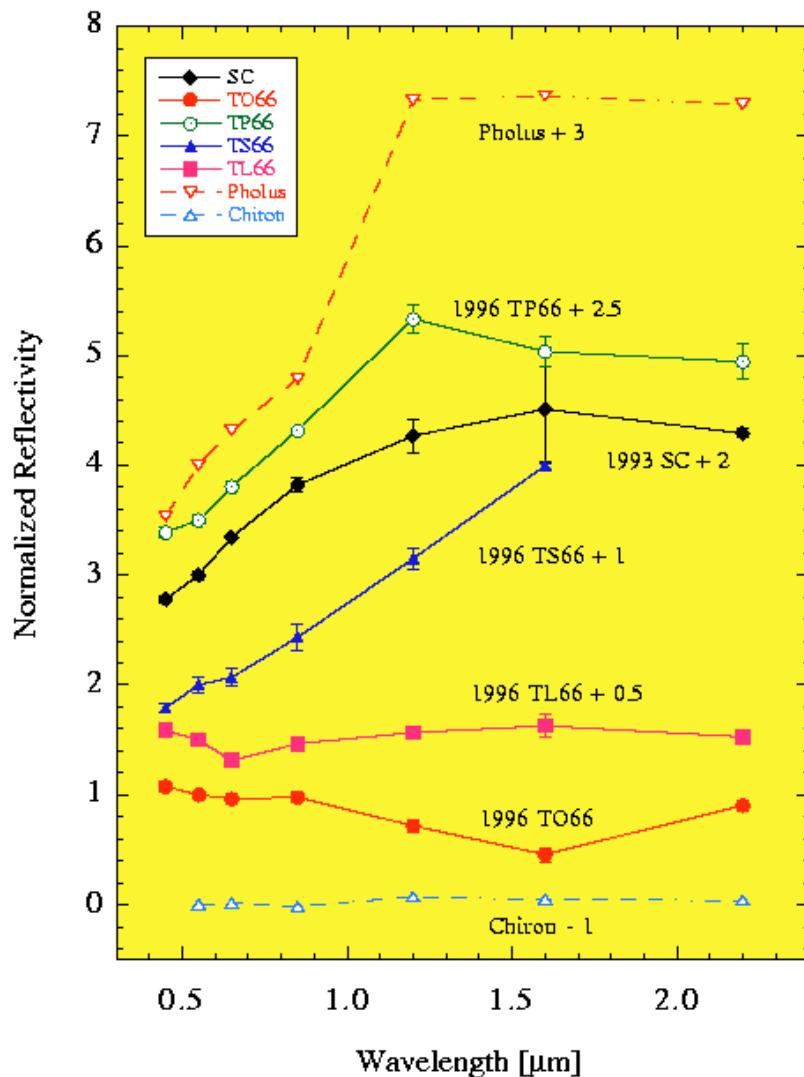


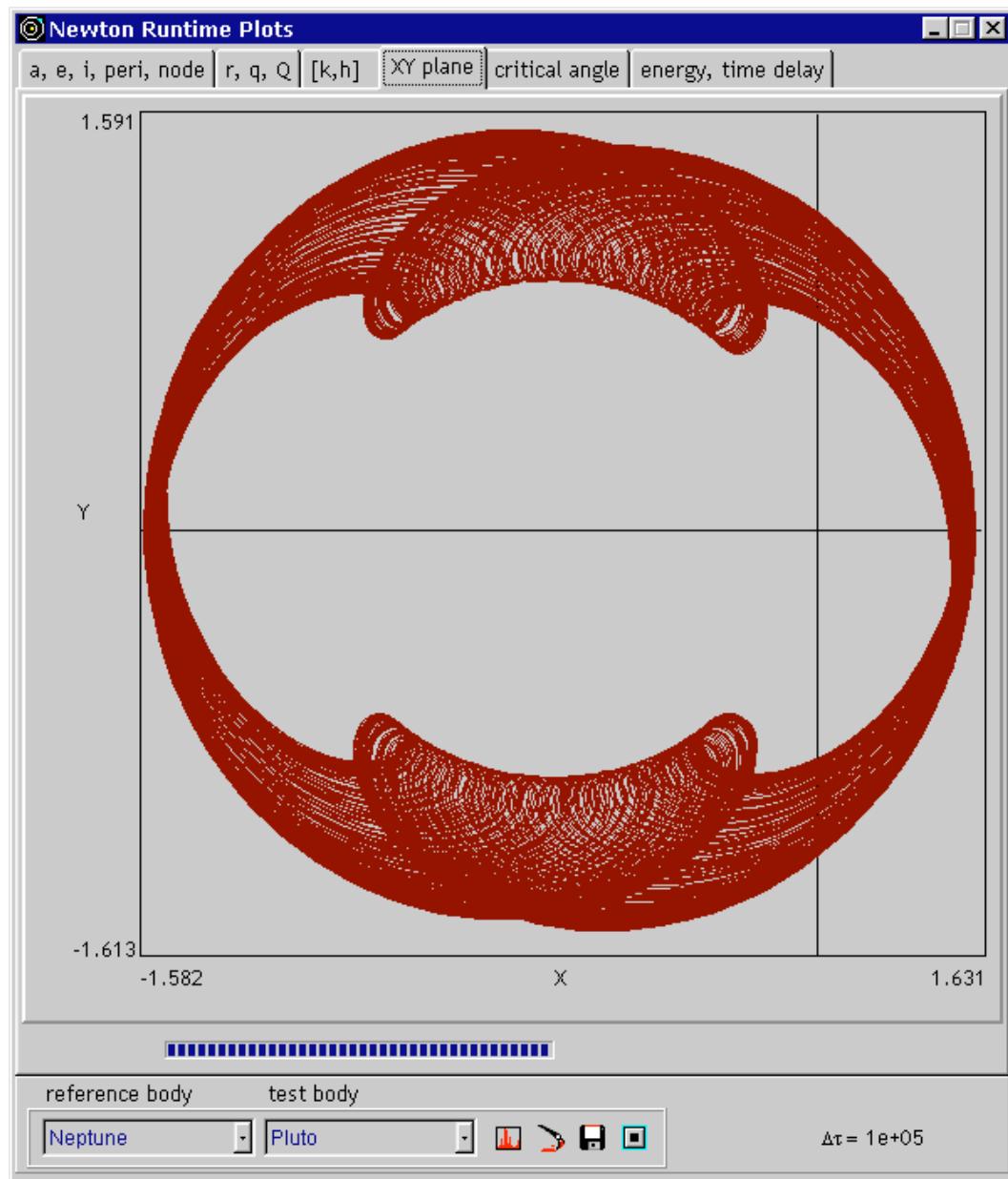
Fig 3: Luu & Jewitt, AJ Nov 1996

TNO Broadband Colors

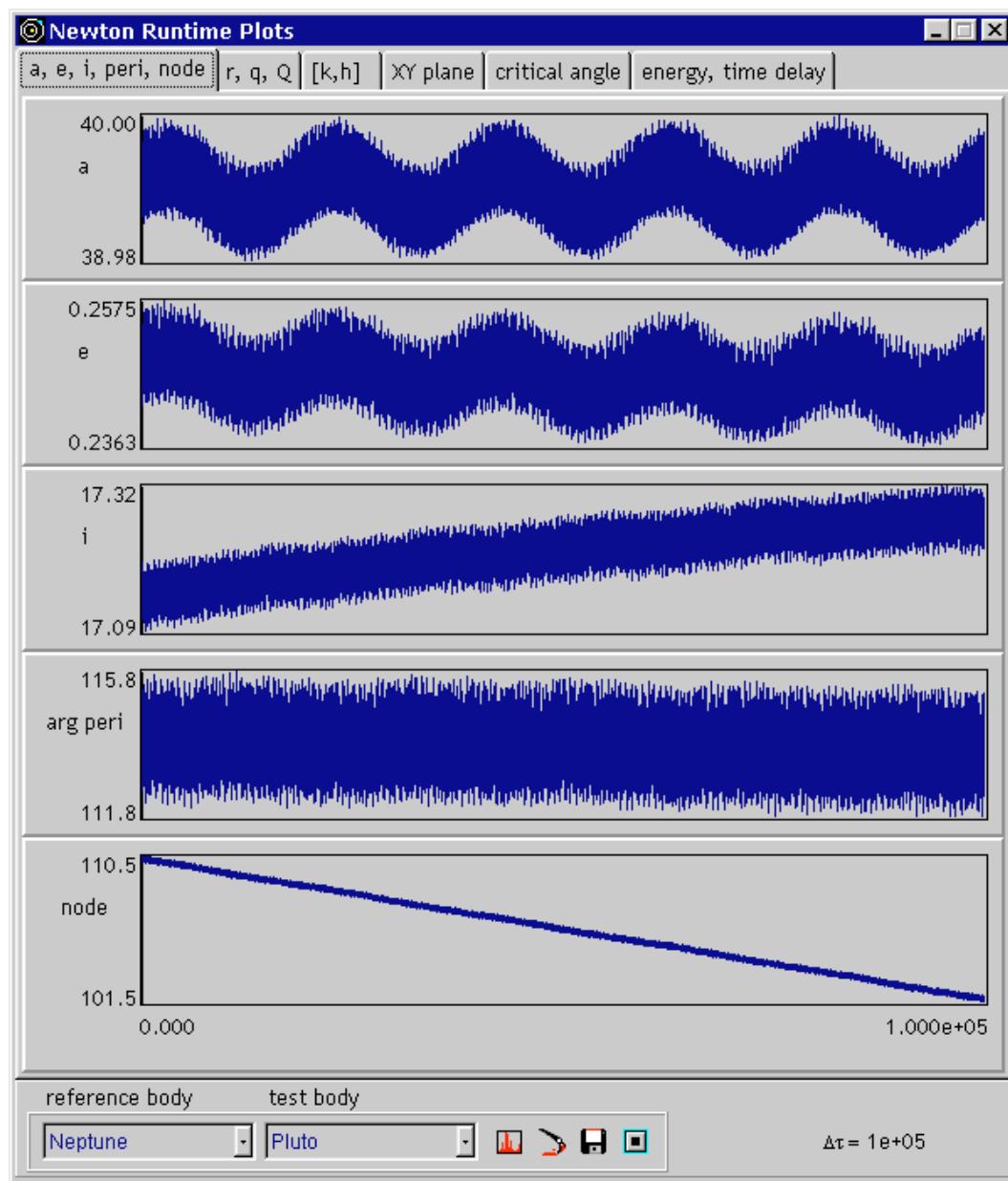


Jewitt and Luu (1998). Astron. J. Fig 1

2:3 Resonance (*Pluto*)

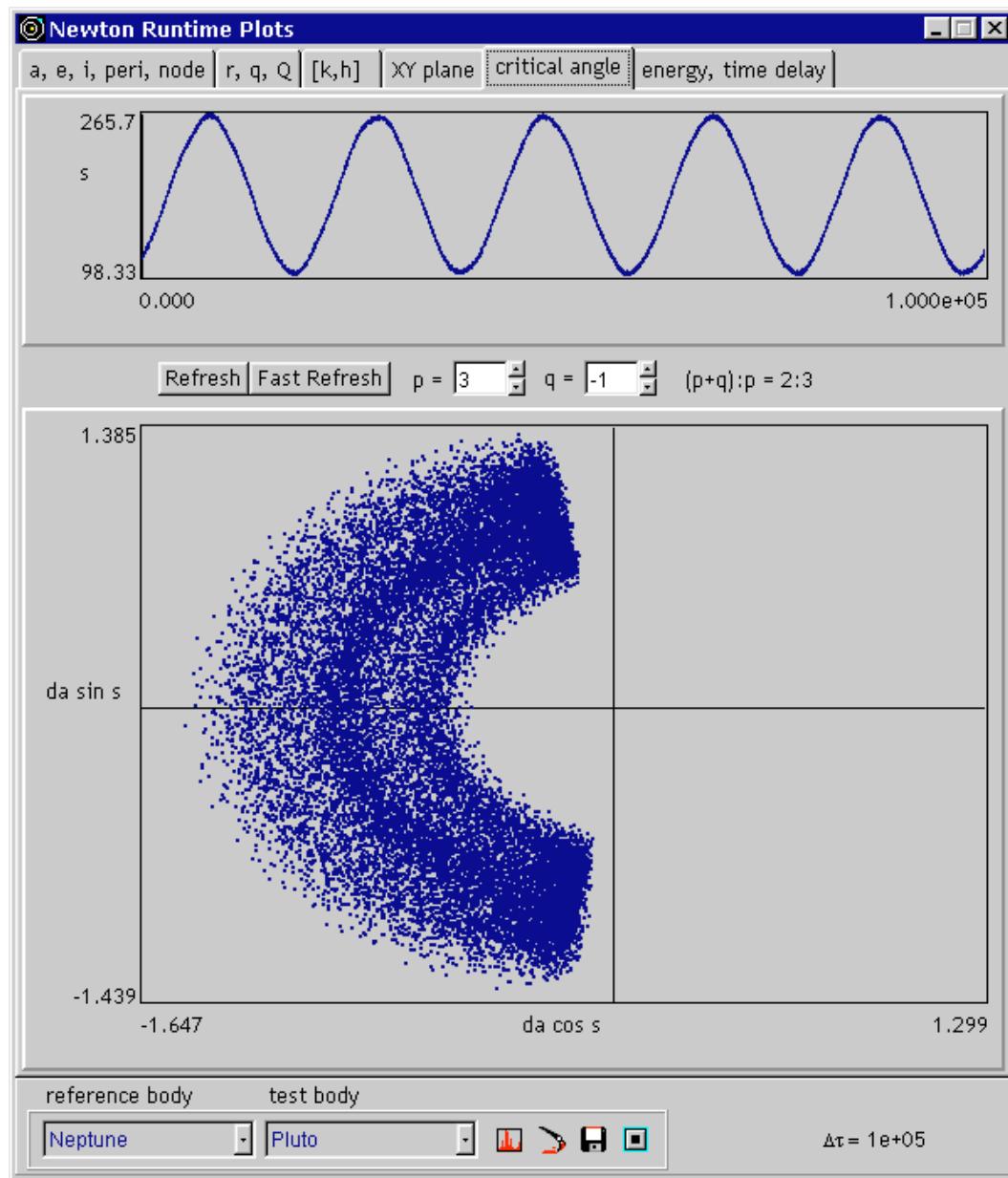


Pluto Orbital Elements

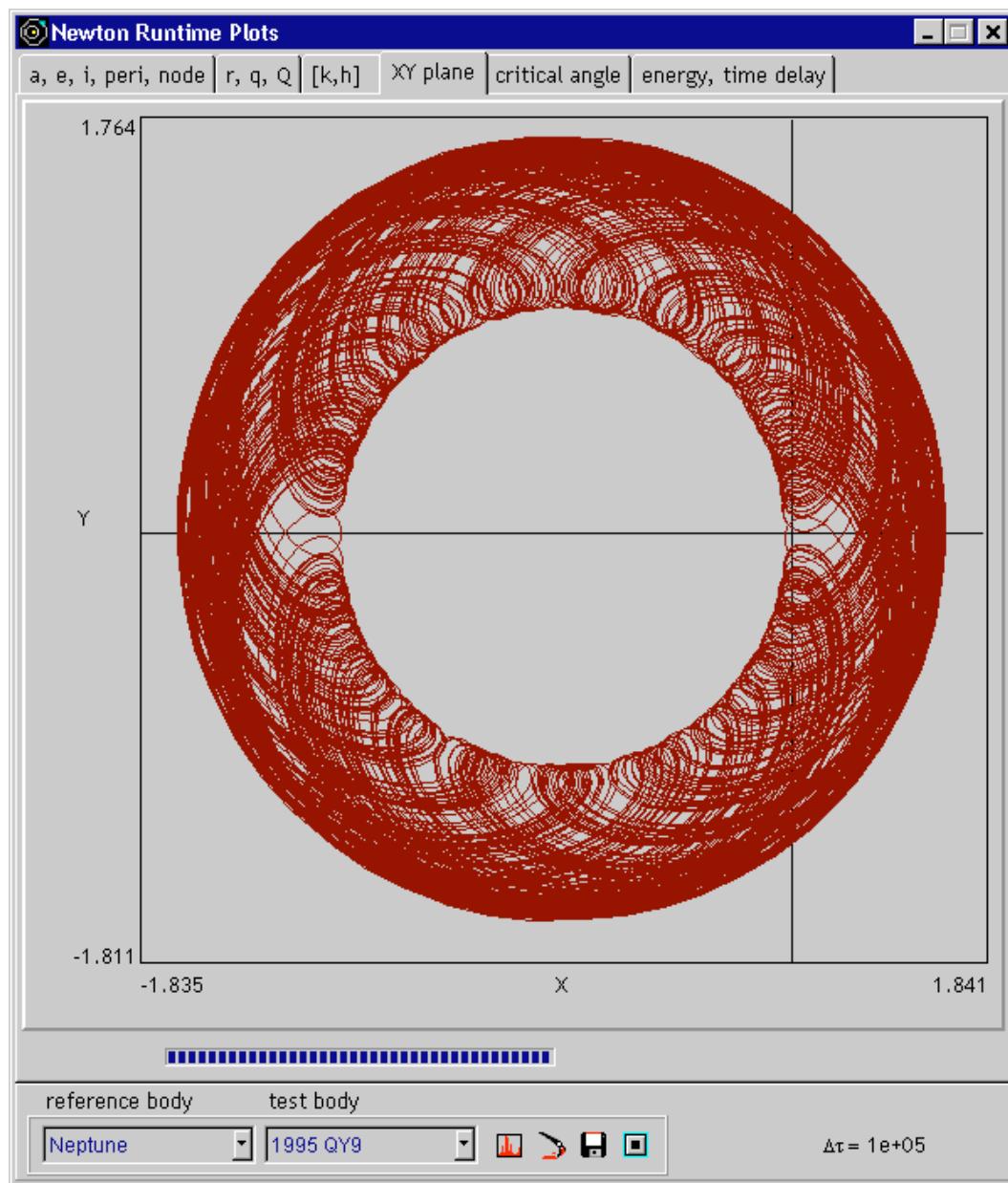


Pluto Critical Angle

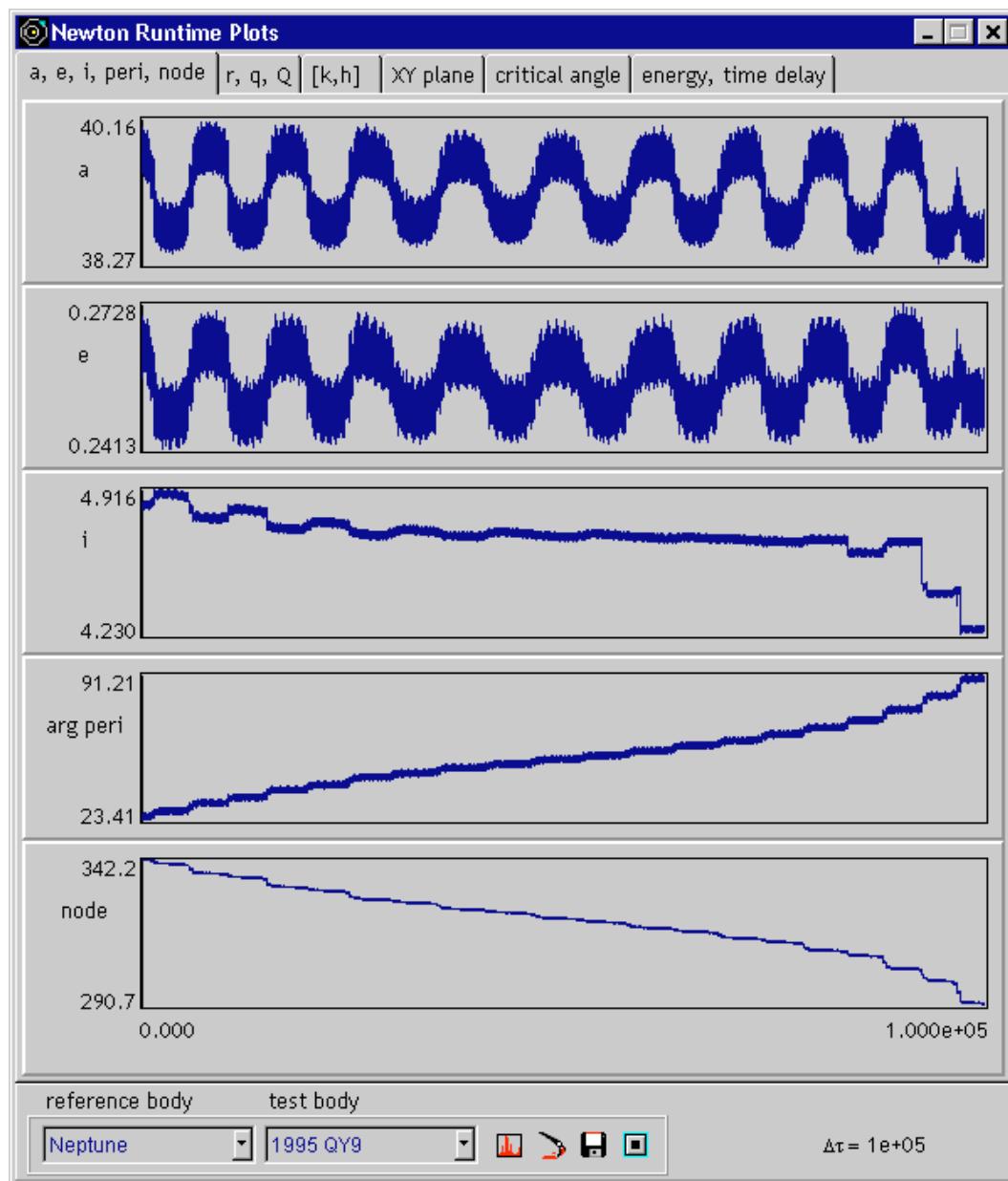
$$\sigma = (p+q)L_{ref} - pL - q(\omega + \Omega)$$



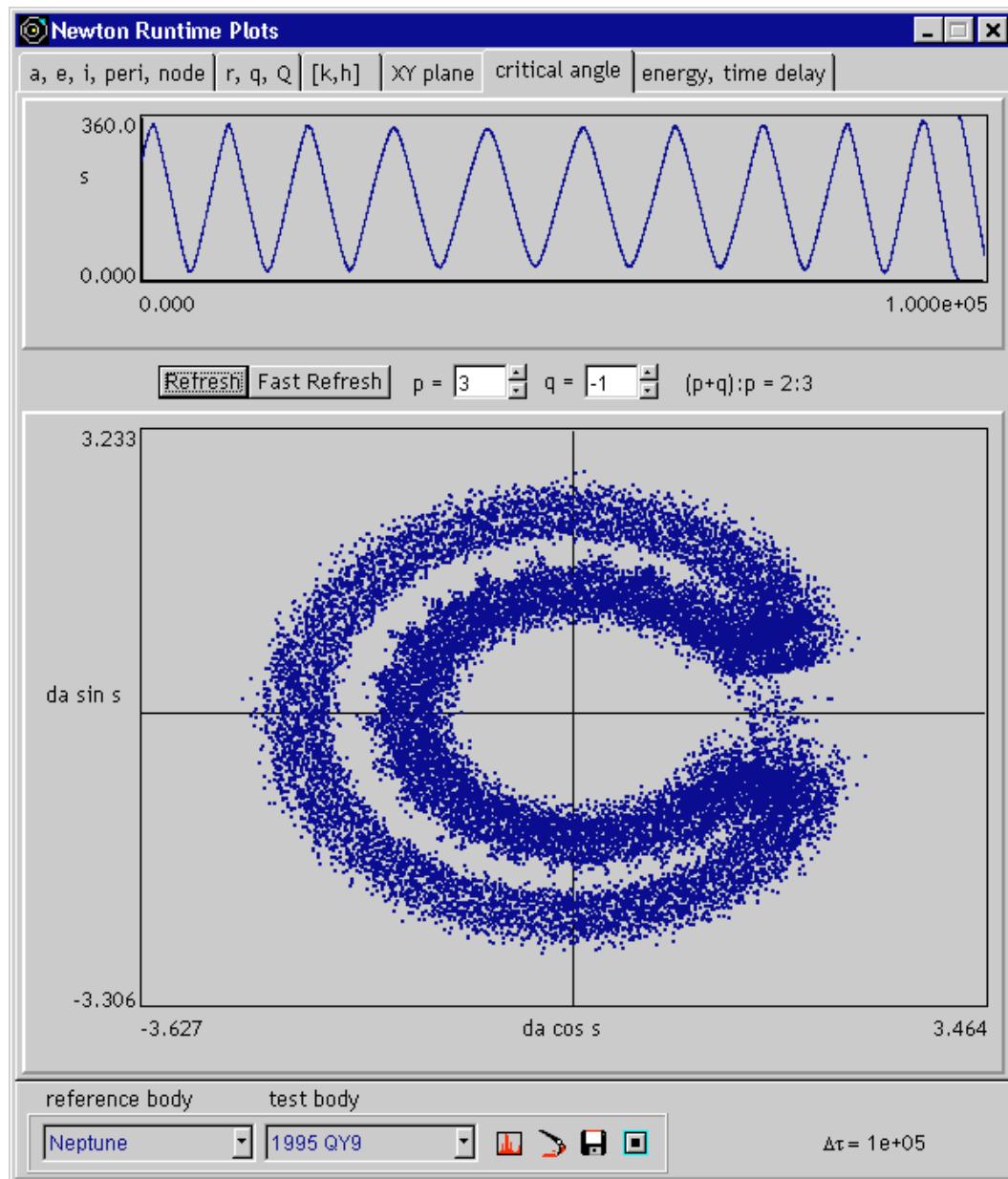
2:3 Resonance (1995 QY₉)



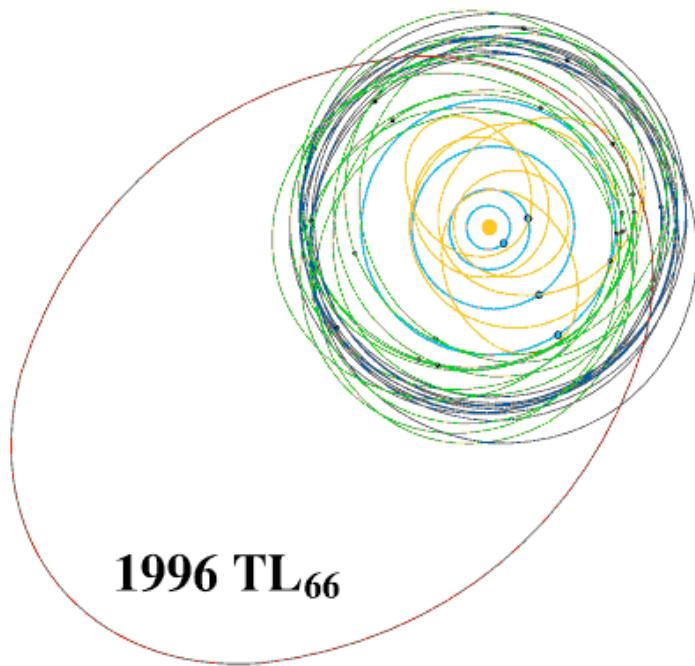
1995 QY₉ Orbital Elements



1995 QY₉ Critical Angle



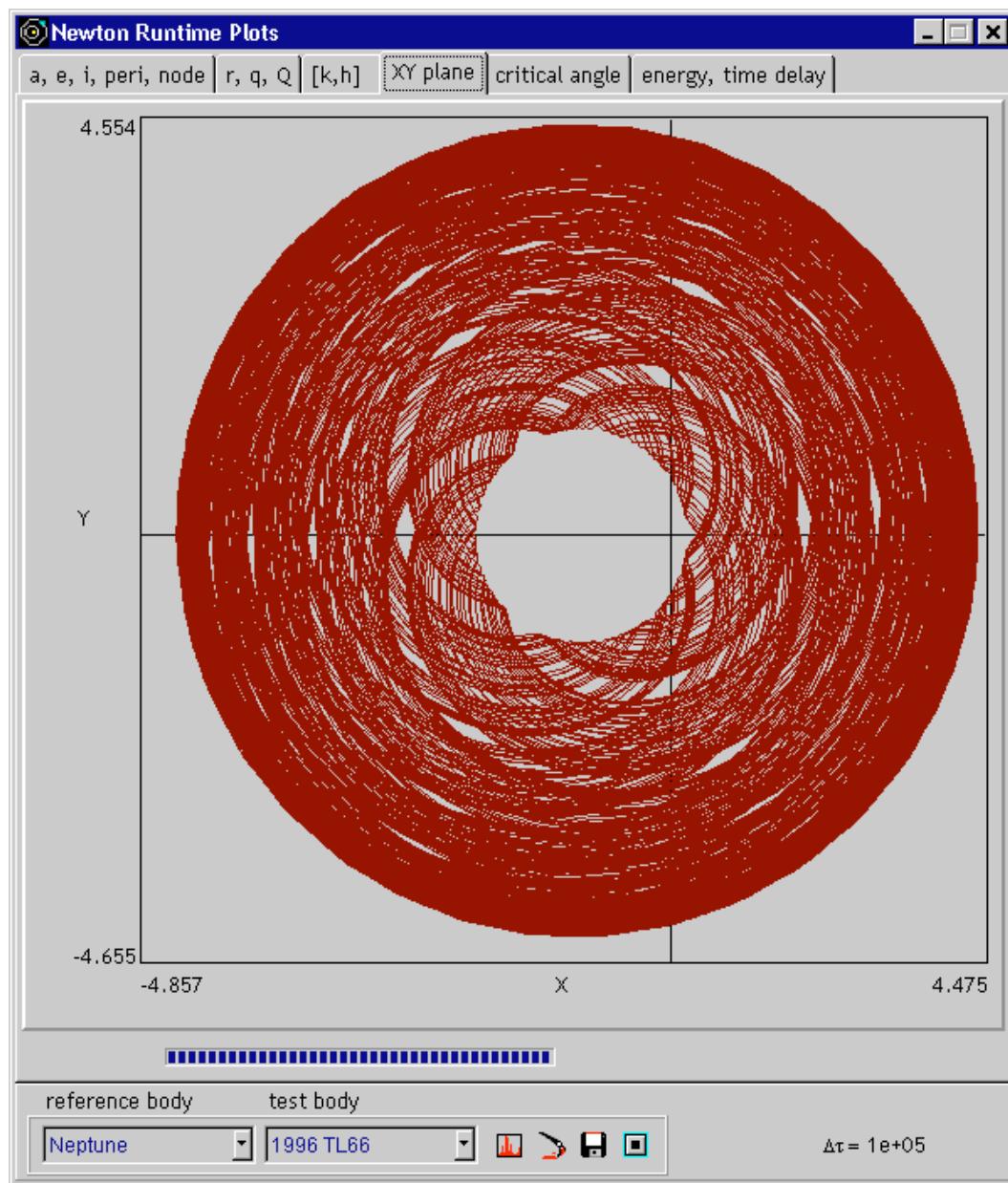
The Orbit of 1996 TL₆₆



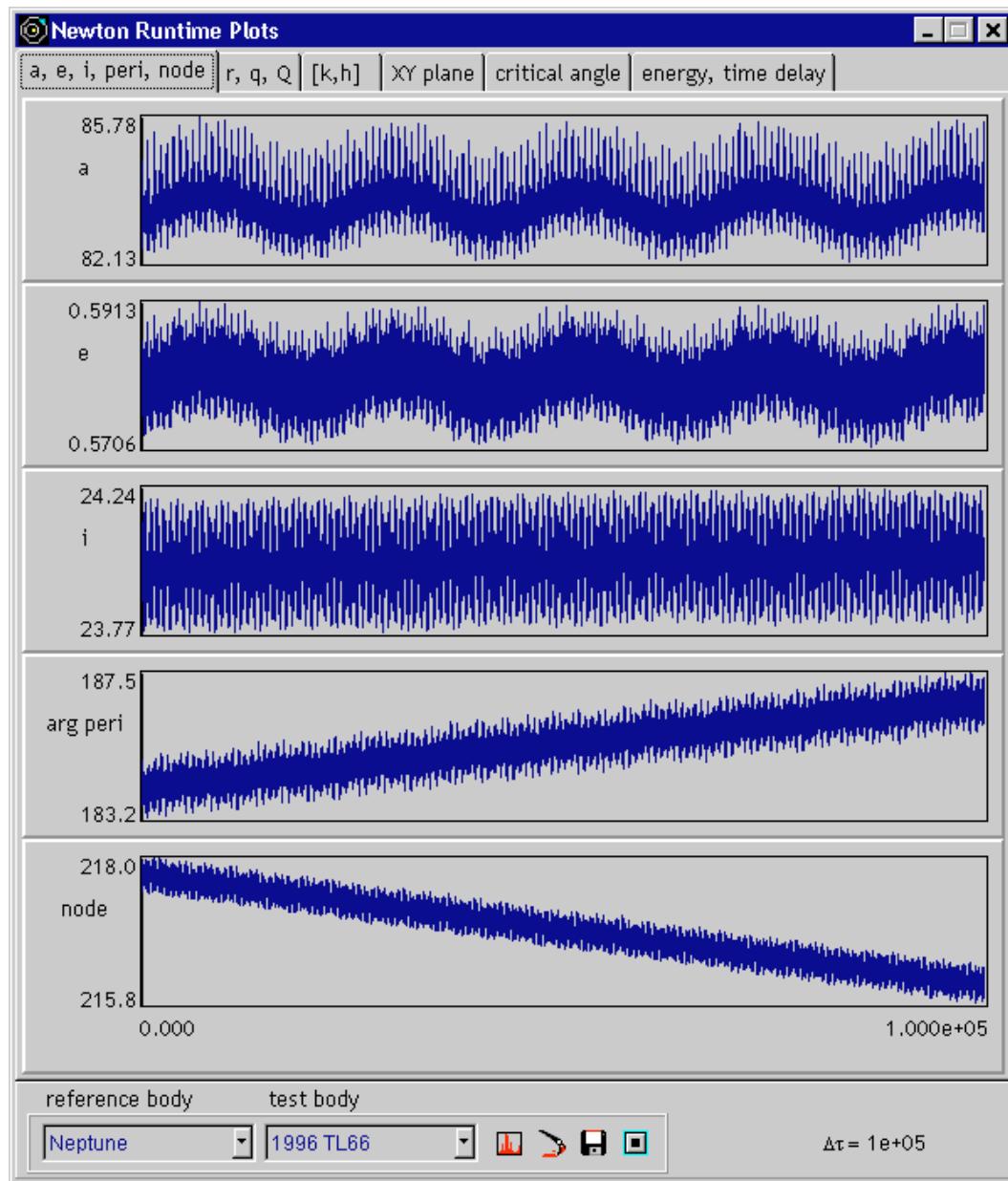
Minor Planet Center

Plot prepared on 1997 June 5

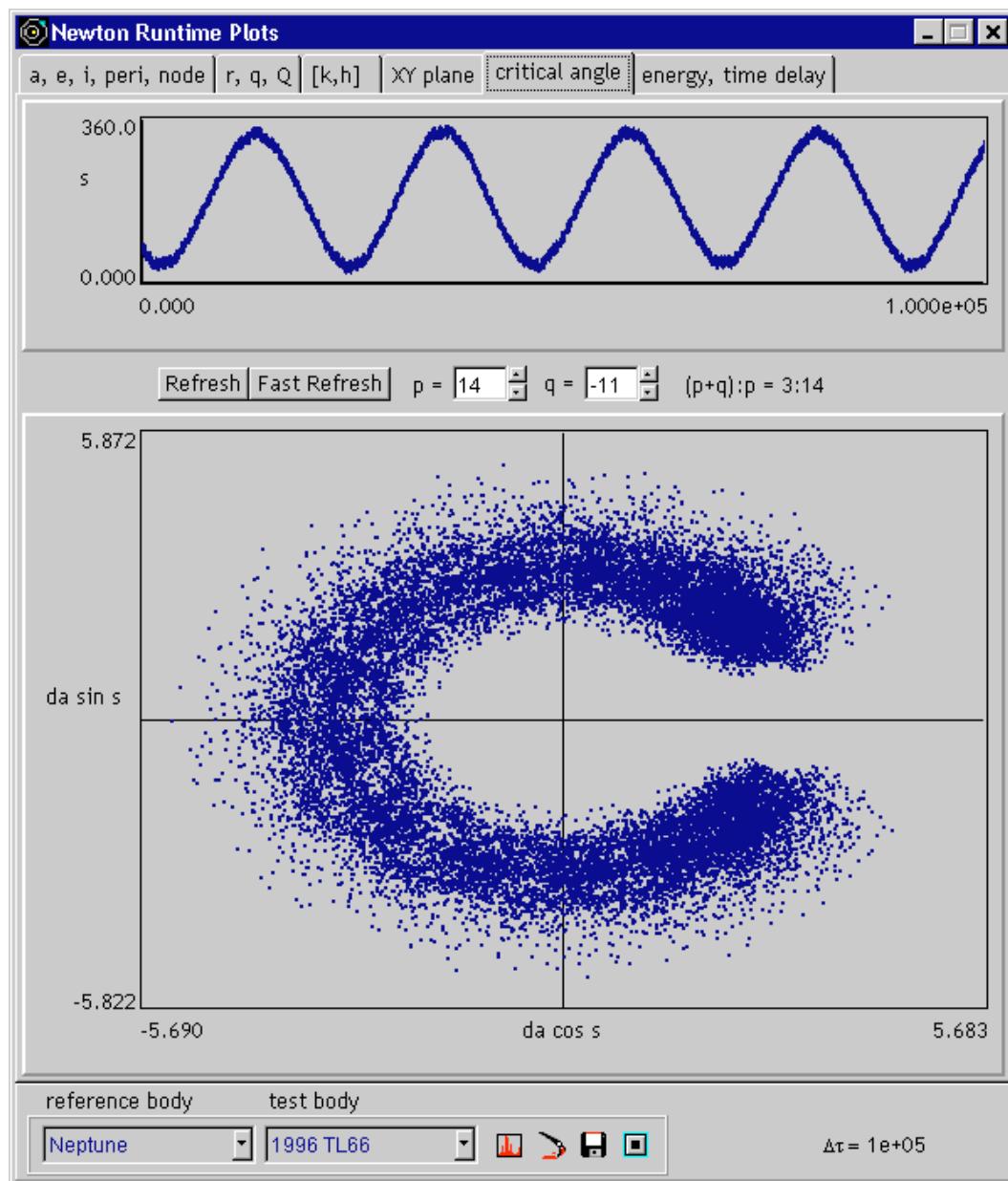
The Peculiar Orbit of 1996 TL₆₆



1996 TL₆₆ Orbital Elements

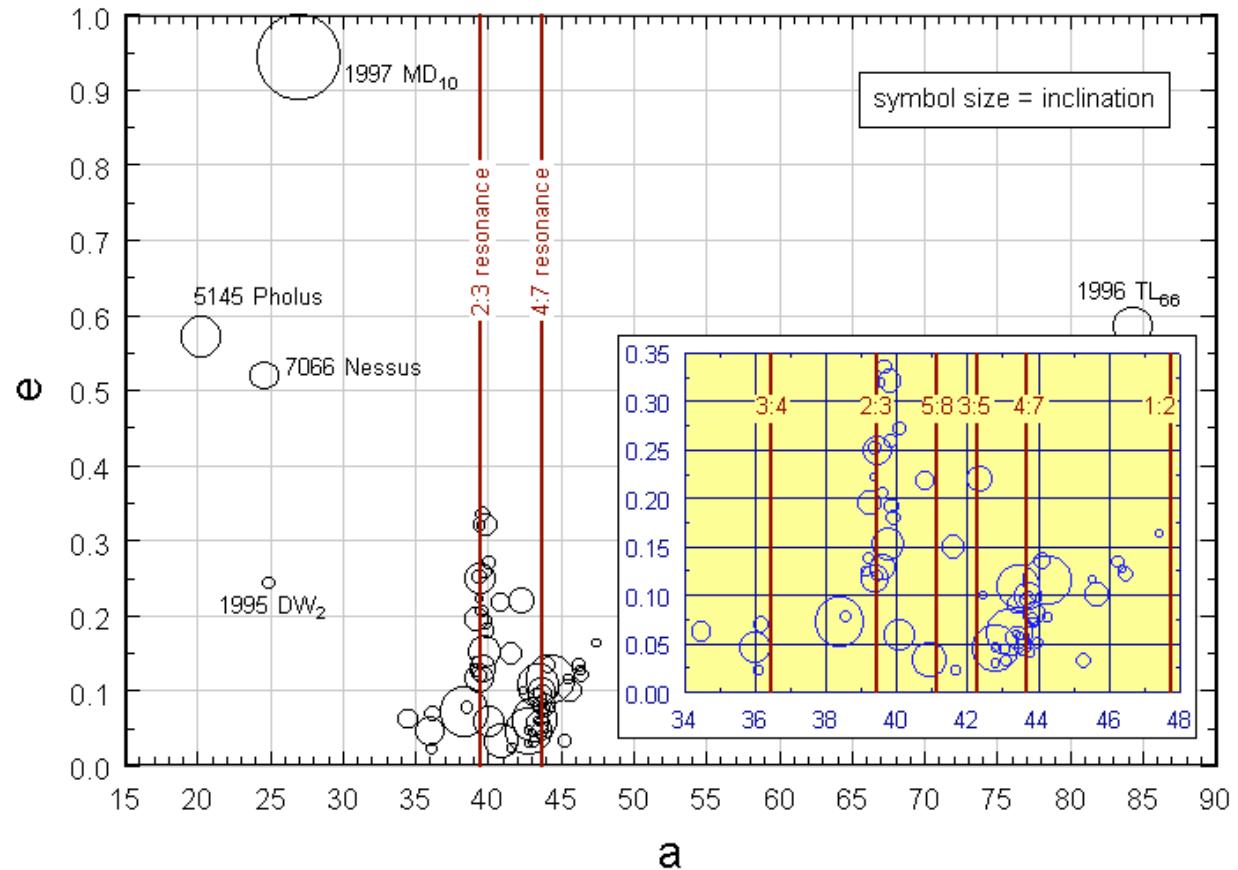


1996 TL₆₆ Critical Angle

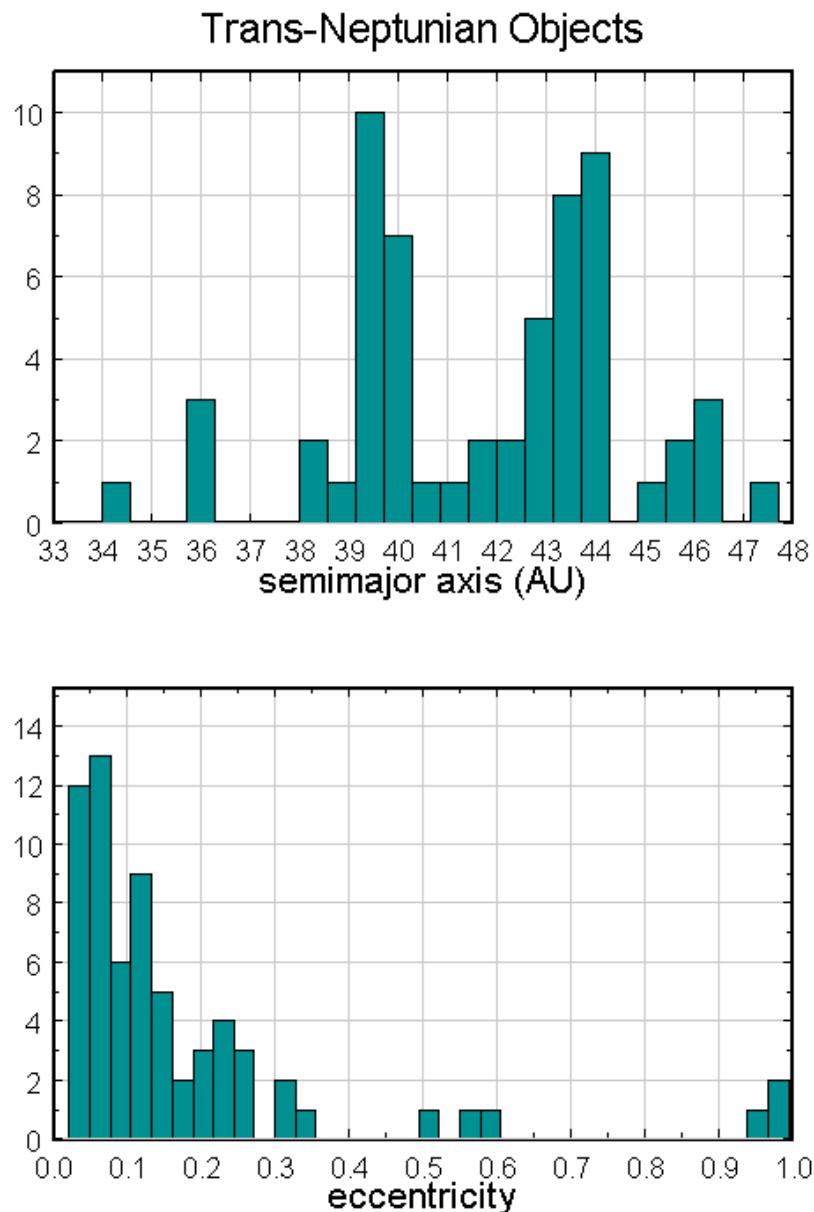


TNOs in a - e Space

Trans-Neptunian Objects



TNO Distributions



Resonance Sweeping and Capture (Malhotra)

- Suppose a mass M scatters a planetesimal m , ejecting it from the system. Then angular momentum conservation requires

$$-\frac{\delta a}{a} \propto \frac{m}{M}$$

- A single planet would, on average, suffer zero net change in orbital radius.
- But the four Jovian planets act together to evolve differently (numerical simulations of Fernandez & Ip, 1984): Jupiter shrinks slightly in radius, while Saturn, Uranus, and Neptune increase significantly in radius.
 - Planetesimals get handed down, planet to planet, until they reach Jupiter, which is very efficient at scattering outward.
 - Rescattered (by Neptune) objects have a bias towards larger angular momentum, stolen from Jupiter.
 - Hence, Neptune (and Uranus and Saturn) gains angular momentum.

Resonance Sweeping and Capture (Malhotra)

- Hence, low-order mean-motion resonances exterior to Neptune sweep through the primordial objects in the outer solar system, collecting them in the process.
 - Resonance capture is a common phenomenon.

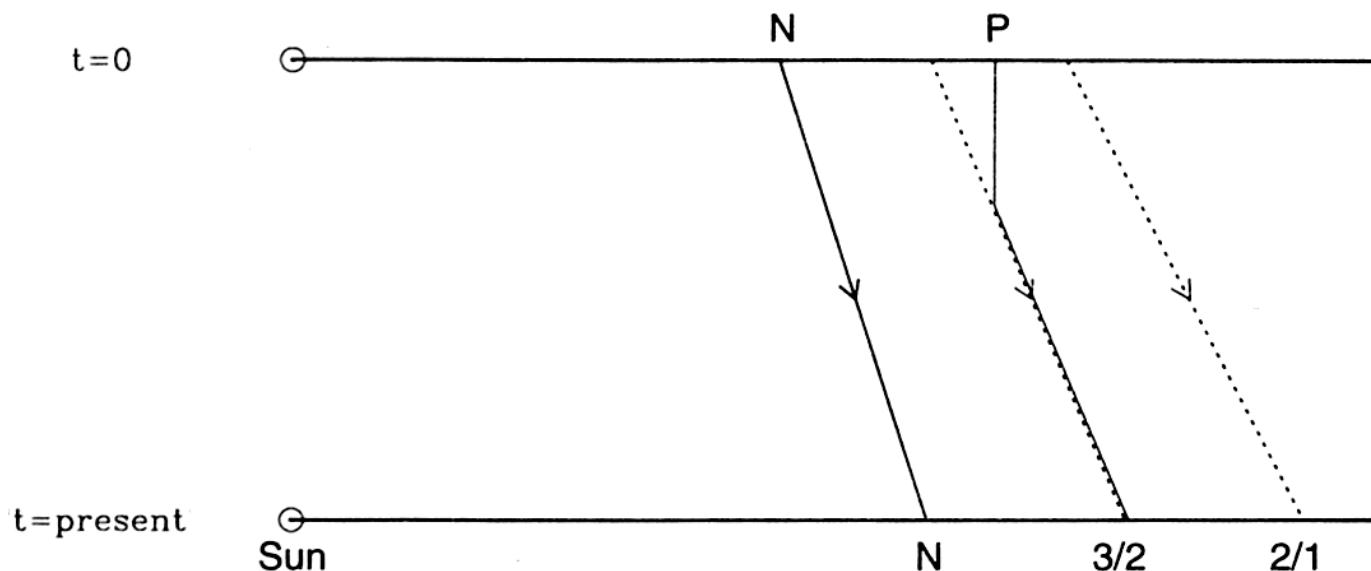
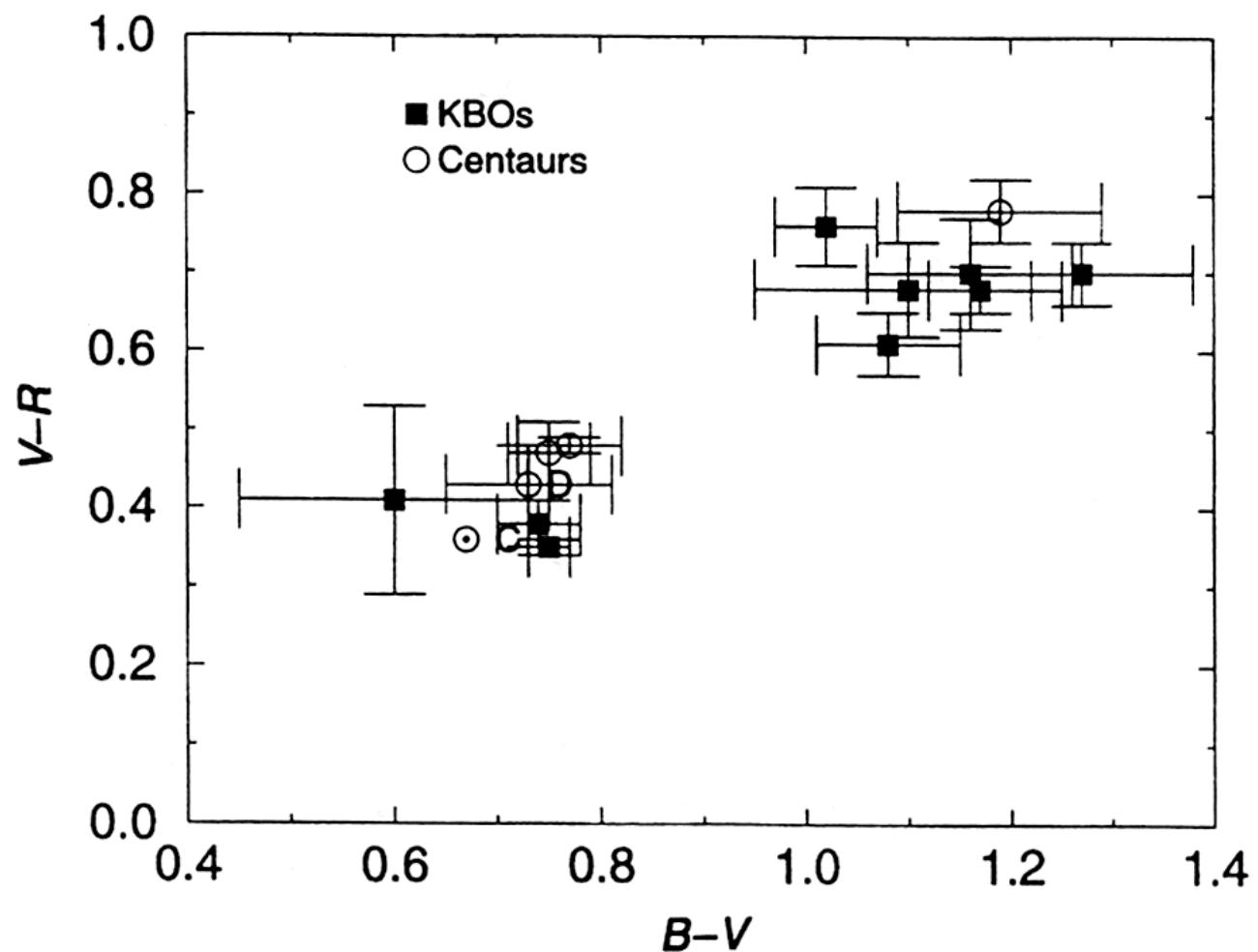


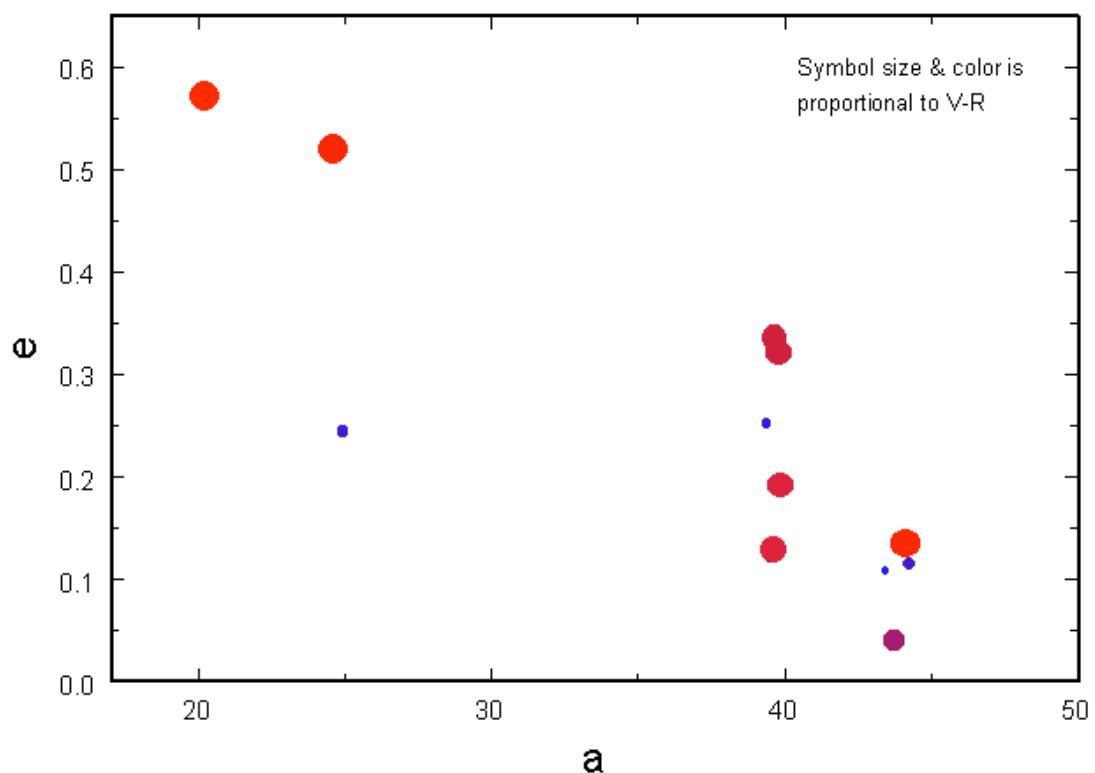
FIG. 1. A schematic diagram to illustrate the outward radial migration of Neptune and its exterior orbital resonances during the late stages of planet formation. The distance from the Sun is along the horizontal direction. Neptune's outward orbital migration is shown along the path marked N–N. For clarity, only two first-order resonances (3:2 and 2:1) are shown (dotted lines). A “Pluto” in an initially circular, nonresonant orbit beyond Neptune could have been captured into the 3:2 resonance and would evolve along the solid line path indicated by P—3/2.

Bimodal Color Distribution



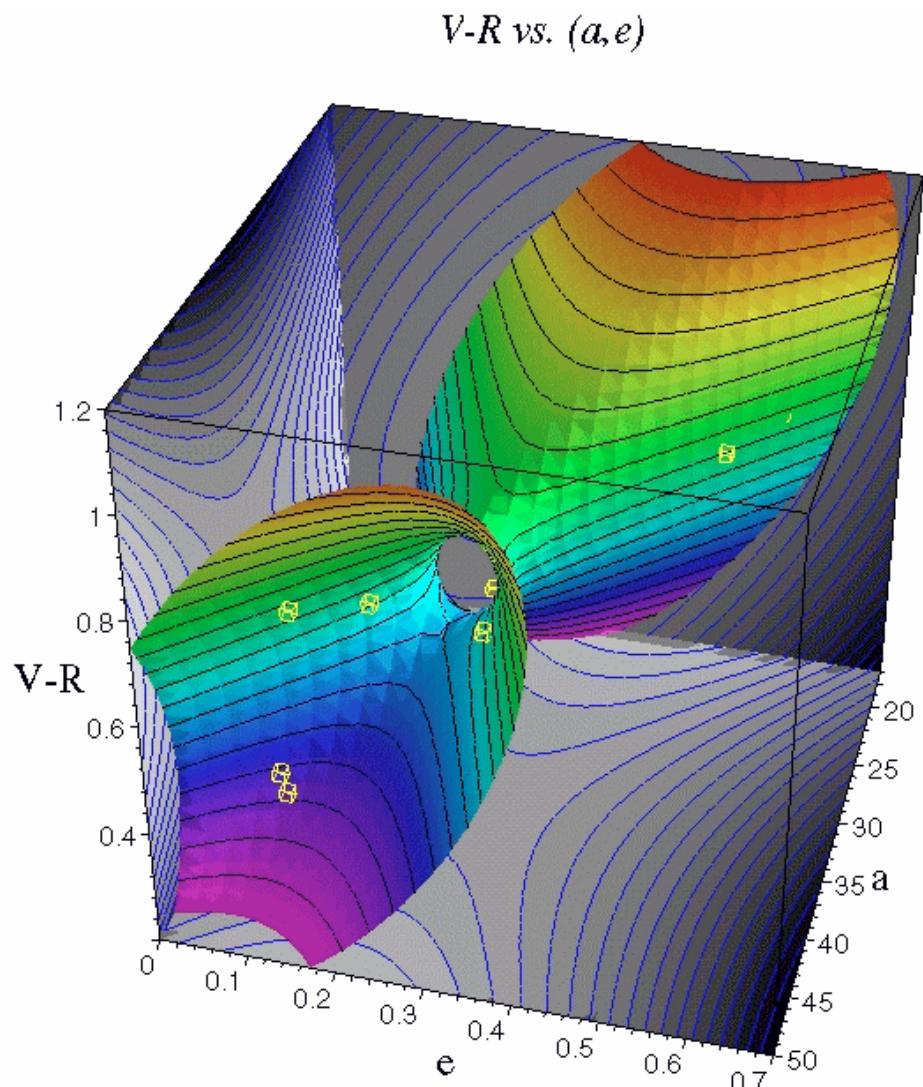
Bimodal Color Distribution

- No obvious correlation with orbital elements...



Bimodal Color Distribution

- ...or is there?



$$ax^2 + by^2 + cz^2 + dxz + eyz + fxz + gx + hy + kz + l = 0$$